

CO-FIRING BOSNIAN COALS WITH WOODY BIOMASS: EXPERIMENTAL STUDIES ON A LABORATORY-SCALE FURNACE AND 110 MW_e POWER UNIT

by

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This paper presents the findings of research into cofiring two Bosnian coal types, brown coal and lignite, with woody biomass, in this case spruce sawdust. The aim of the research was to find the optimal blend of coal and sawdust that may be substituted for 100% coal in large coal-fired power stations in Bosnia and Herzegovina.

Two groups of experimental tests were performed in this study: laboratory testing of co-firing and trial runs on a large-scale plant based on the laboratory research results. A laboratory experiment was carried out in an electrically heated and entrained pulverized-fuel flow furnace. Based on and following the laboratory research findings, a trial run was carried out in a large-scale utility – the Kakanj power station, Unit 5 (110 MW_e), using two mixtures; one in which 5 wt.% and one in which 7 wt.% of brown coal was replaced with sawdust. Compared to a reference firing process with 100% coal, these co-firing trials produced a more intensive redistribution of the alkaline components in the slag in the melting chamber, with a consequential beneficial effect on the deposition of ash on the superheater surfaces of the boiler. The outcome of the tests confirms the feasibility of using 7 wt.% of sawdust in combination with coal without risk to the efficiency of the unit, its combustion process and with the benefits of emissions reductions. Furthermore, they show that no modification to the existing coal transport system and boiler equipment is necessary to achieve this outcome.

Key words: *co-firing, coal, woody biomass, ash, deposits, slagging, NO_x emission, SO₂ emission*

Introduction

As set out in the European Commission's white paper [1], in the short-to-medium term, the co-combustion of biomass and bio-waste in coal-fired power plants is one of the most straightforward biomass applications. The main reasons for using biomass as co-fuel is

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its dual role in greenhouse gas mitigation, as a substitute for fossil fuels (bio-energy) and as a carbon sink, [2]. Fuels derived from biomass also contain less sulfur or trace elements. Current research on co-combustion is focused on controlling combustion behaviour, emissions, corrosion, agglomeration, and fouling-related problems. Biomass for combustion in industrial-scale furnaces must meet a number of criteria, including availability throughout the year to ensure security of supply, high density to minimize transportation costs, sufficiently high heating value, and acceptable price, [2]. Wood residue meets these requirements, [2-4]. In the last decade, significant progress has been made in the utilisation of biomass in coal-fired power stations. Over 250 units in the world have either tested or demonstrated co-firing of biomass or are currently co-firing on a commercial basis, [5]. Coal is often replaced with up to 30% by weight of biomass in pulverised coal plants, as in Belgium, Canada, Denmark, Finland, The Netherlands, Sweden, United Kingdom, Germany, Poland and The United States. Most of these projects are related to co-firing with biomass of high-ranked coal (both bituminous and anthracite), while co-firing of low-ranked sub-bituminous coal and lignite with biomass is more limited, *e.g.* those projects involving Greek lignite reported in [6].

This paper presents research into ash-related problems and emissions during co-firing low-rank Bosnian brown coal and lignite with woody biomass. The aim of the research was to find the optimal blend of coal and sawdust in two large coal-based power stations in Bosnia and Herzegovina; the Kakanj power station (2×110 MW_e, 1×230 MW_e) which uses low-rank brown coal and the Tuzla power station (1×100 MW_e, 2×200 MW_e, 1×215MW_e) which uses mostly lignite.

Experimental

Lab-scale tests

Lab-scale furnace configuration

The 20 kW lab-scale furnace, the electrically heated entrained pulverized-fuel (PF) flow furnace depicted in fig. 1, was used for the laboratory experimental tests. The possibility of the process temperature setting in the range from the ambient to 1560 °C was the main feature of the experimental facility. That ability was provided by SiC-type electric heaters controlled by a central programmable logic controller (PLC) and thiristor units connected to the PLC digital outputs for each particular heating zone of the furnace [7, 8].

Various types of coal and sawdust were used. The appropriate particle sizes of the mixtures were obtained using a laboratory hammer mill. The pulverized fuel particles were fed into the furnace by means of a volumetric-type feeder, equipped with a speed controller, allowing mass flow in the range of 0.25–5.25 kg/h. The air for combustion from the blower was split into primary air, secondary air, tertiary air and over-fire air (OFA). The first three air portions were introduced into the furnace over a burner placed at the top, enabling downward flow of the air-fuel particles mixture. The final air portion, or OFA, was used to investigate the air stage combustion, by simulating the OFA system used in large boilers. It was consequently introduced directly into the reaction tube (see fig. 1). The excess air ratio was adjusted by controlling the air flow in each particular air line at constant fuel flow rate. For more details, see [7, 8].

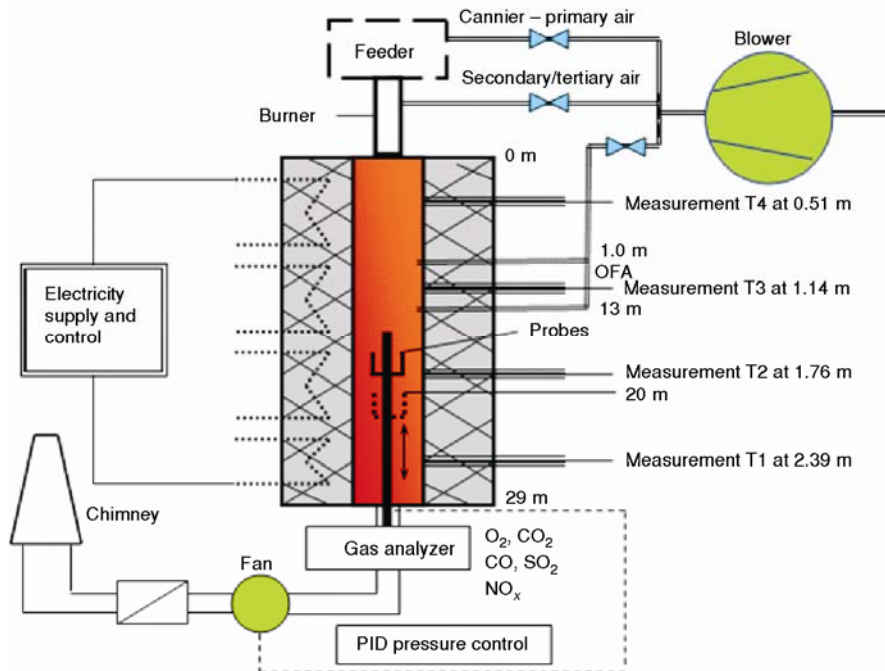


Figure 1. Schematic layout of the furnace used for the co-firing tests in the laboratory

Fuels tested on lab-scale furnace

The co-firing tests used spruce sawdust in combination with Kakanj brown coal and a lignite blend consisting of Dubrave lignite and Sikulje lignite. Coal-sawdust mixtures at 93:7 wt.% and 80:20 wt.% were tested. The resultant co-firing fuel test matrix is given in tab. 1.

Table 1. Fuel co-firing options

Fuel	Fuel type	Symbol	[wt.%]	Thermal input [%]
Spruce sawdust	Biomass	S	100	100
Dubrave-Sikulje lignite	Lignite	L	100	100
Kakanj brown coal	Brown coal	K	100	100
Blend of Kakanj brown coal with spruce sawdust	Blend	K93S7	93:7	89:11
Blend of Kakanj brown coal with spruce sawdust	Blend	K80S20	80:20	72:28
Blend of Dubrave-Sikulje lignite with spruce sawdust	Blend	L93S7	93:7	88:12
Blend of Dubrave-Sikulje lignite with spruce sawdust	Blend	L80S20	80:20	70:30

Table 2 presents proximate and ultimate analyses of the fuels tested. Comparison of the results for the coal and sawdust suggests that the main difference between them relates to the ash content, as the coal types tested have very high ash content compared to that of the sawdust. This has a significant influence on the combustible content and calorific value of the fuels. On the other hand, the biomass sample has a very high volatile content, which may be expected to accelerate the combustion process, while the coal types have a much higher fixed carbon concentration. Finally, the wood sample has significantly lower sulphur content [7, 8].

Table 2. Proximate and ultimate analyses of the fuels tested on lab-scale furnace

Fuel	L	K	S	L93S7	L80S20	K93S7	K80S20
<i>Proximate analysis, %, as-received</i>							
Moisture	34.22	11.30	11.20	32.60	29.61	11.29	11.28
Ash	23.62	41.43	0.26	21.99	18.95	38.55	33.20
Volatiles	24.32	25.88	75.48	27.90	34.55	29.35	35.80
Fixed C	17.42	21.39	13.06	17.11	16.55	20.81	19.72
<i>Ultimate analysis, %, as-received</i>							
Carbon	29.58	35.11	38.91	30.23	31.44	35.38	35.87
Hydrogen	2.49	2.78	7.36	2.83	3.47	3.10	3.70
Sulphur	0.73	2.28	0.33	0.71	0.65	2.14	1.89
Nitrogen	0.48	0.96	0.33	0.47	0.45	0.92	0.83
Oxygen	9.29	7.03	41.61	11.55	15.75	9.45	13.95
<i>Heating value, kJ/kg, as-received</i>							
Net	8588	12657	15612	10009	10793	13022	13700

Table 3. Ash chemical composition of the fuels tested on lab-scale furnace

Component	L	K	S	L93S7	L80S20	K93S7	K80S20
SiO ₂	49.88	43.23	21.30	49.86	49.79	43.22	43.18
Al ₂ O ₃	24.16	19.13	4.80	24.14	24.10	19.12	19.10
Fe ₂ O ₃	10.42	10.40	2.79	10.41	10.40	10.40	10.39
CaO	4.41	12.60	14.6	4.45	4.54	12.62	12.66
MgO	3.18	2.97	11.6	3.18	3.19	2.97	2.98
K ₂ O	1.61	1.13	41.6	1.62	1.63	1.13	1.14
Na ₂ O	0.13	0.66	0.78	0.13	0.13	0.66	0.66
TiO ₂	0.83	0.71	0.13	0.83	0.83	0.71	0.71
SO ₃	4.38	5.36	< 0.05	4.38	4.37	5.36	5.35

In tab. 3, the ash chemical analyses of the coals and the spruce sawdust tested, presented through their oxides content, are given. Compared to the coal types tested, the spruce sawdust has very high potassium content in its ash, which could cause serious ash deposition problems. The distribution of alkaline metals and the lower content of silica and alumina compounds are anticipated to reduce the ash fusion temperature of the sawdust sample.

Test runs in the laboratory

In each co-firing run in the laboratory, sawdust was mixed with coal, the fuel mixture was pre-dried at approximately $w = 0\%$, milled to the specific particle size range and then supplied into the feeder tank of the furnace [7, 8]. Fuel thermal load was kept at approximately 5 kW_t in all runs. Process temperature varied from 880 to 1550 °C and excess air ratio from 0.95 to 1.4. Depending on the kind of fuel used and excess air amount, the total airflow rate was between 4.29 and 6.60 m_n³/h. The primary (carrier) air flow rate was set at 1.50 m_n³/h for all runs, with the rest of the air divided into secondary and tertiary portions, at a ratio of 2.6:1. NO, NO₂, SO₂ and CO emissions were measured by a Gas analyser (TESTO 350 instrument with an integrated TESTO 339 dry unit) in ppm, and then converted to mg/m_n³, dry, 6% O₂. Measurements were repeated several times during each test (in periods of 90 minutes) to eliminate the influence of accidental phenomena. The estimated measurement error was 18 ppm (2.8%) for the NO_x emissions and 59 ppm (2.6%) for the SO₂ emissions. Flue gas temperature was measured at the defined point in the partially insulated outlet tube. Depending on the test run, the temperature of the gas ranged from 50 and 140 °C.

The processes in the flue gas line were frozen; there was neither post-combustion nor air suction from the reactor to the Gas analyser. There was sufficient combustion efficiency under all co-firing processes, with burning out in ash deposits at 96.5 to 99.5% for brown coal–sawdust co-firing, and app. 99% for lignite-sawdust co-firing processes.

Applicability and reliability of the laboratory tests results

Relating to the real situations in the boiler, the results presented here are valid for cross flow around the tubes of the heat exchangers and for the refractory walls of the combustion chamber. With regard to vertical walls and particles flowing parallel to them, the probes should be set at appropriate angles with regards to the particle flow direction, and tests related to this issue will be performed in the future. Only the initial stage of the slagging (sampling of 45-90 minutes duration) has been examined here. Also, it should be noted that as a result of the combustion, the coal particles temperature can possibly be higher than the measured reactor wall temperature, which may affect ash transformation and the deposition process. Furthermore, specific particle size distribution (see tab. 4), as well as specific air distribution were used during the tests [7, 8].

Trial run at Kakanj power plant Unit 5-110 MW_e

Characteristics of Boiler Kakanj power plant Unit 5

Based on the laboratory research findings, a trial co-firing was completed at the Kakanj power station unit 5 (110 MW_e), which is equipped with PF boiler with slag tap furnace, hammer mills and low NO_x swirl burners, fig. 2, and fuelled with brown coal from the nearby coal mines of Middle Bosnia.

Eight different types of brown coal are used in an appropriate coal blend, prepared and homogenized on the coal depot. The coal is transported from the coal depot to the boiler bunkers by belt conveyers. Then it is pulverized in the hammer mills, and dried by the hot air before introducing into the boiler over the coal burners. Thus, temperature of PF coal-air mixture obtained in the duct prior to the coal burners is approximately 150 °C (the coal was low-volatile).

The unit was fully reconstructed in 2003, when a new combustion system with low NO_x swirl burners and OFA system was installed, and boiler efficiency increased up to 91%. Temperature in the slag chamber of the furnace has been reduced following the reconstruction from its previous level of 1550 °C to 1450 °C at maximal load. Consequently, NO_x emissions have been reduced from 1400 mg/m_n³ to approximately 700 mg/m_n³ at 6% O₂ dry, supported by the low NO_x swirl burners and the Over Fire Air system installed.

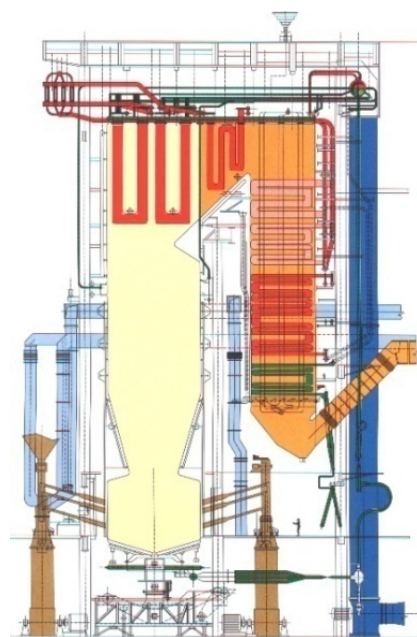


Figure 2. Boiler with slag tap furnace of the Kakanj power plant Unit 5 (110 MW_e)

Co-firing tests and fuel used in trials on Kakanj power plant Unit 5

The trial run was adapted to the brown coal – spruce sawdust mixtures with the sawdust weight ratio of 0%, 5% and 7% (fuel blends U100, U95B5 and U93B7, respectively). Proximate and ultimate analyses of the fuels used in the trial run are given in tab. 4. Spruce sawdust was supplied from the nearby sources by a contracted supplier. The blend of coal and sawdust is prepared at the coal depot, where the fuels are mixed by coal excavators before being transported to the boiler. The fuel mixture was introduced into the furnace over the hammer mills and the coal burners. The load was varied between 70 and 100% of maximal load, operating the unit at a gross electric power output of 75, 90 and 105 MW.

Operational characteristics and parameters recorded during boiler trial run

All measurements on the boiler used in this analysis (measurement of temperatures, flue gas compositions, emissions *etc.*) are operational measurements obtained from the existing modern SIEMENS-XP TELEPERM system installed on the Unit, which has been maintained, checked and revised according to the relevant standards and procedures.

Table 4. Proximate and ultimate analyses of the fuels tested in Trial run

Fuel*	U100	U95B5	U93B7
<i>Proximate analysis, %, as-received</i>			
Moisture	13.90	19.06	18.09
Ash	37.88	34.33	33.05
Volatiles	28.97	29.32	31.16
Fixed C	19.25	17.28	18.59
Combustible	48.22	46.60	48.86
<i>Ultimate analysis, %, as-received</i>			
Carbon	32.62	32.12	33.36
Hydrogen	2.60	2.20	2.52
Sulphur	2.06	1.57	1.59
Nitrogen	0.72	0.81	0.75
Oxygen	10.22	9.91	10.63
<i>Heating value, kJ/kg, as-received</i>			
Gross	13351	12651	13446
Net	12496	11759	12510

*U100 – coal alone, U95B5 – coal 95 wt.% and biomass 5 wt.%, U93B7 - coal 93 wt.% and biomass 7 wt.%

The boiler (block) operation during co-firing was stable for both of the co-firing mixtures, with 5 and 7 wt.% ratio of the sawdust, in the complete range of the load, from a minimum (75 MW) to the maximum load (105 MW). At maximum load (105 MW) in the process with 7 wt.% of spruce sawdust, the temperature of the fuel-air mixture at the exit from the mill was at the lower limit of the allowable range of temperatures (75 °C), possibly due to the higher moisture content in the fuel (the sawdust was wintered at the coal depot because the trial run was delayed in time), but this had no negative impact on the stability of combustion process and boiler operation. At the lower boiler loads, as well as in the process with 5% of sawdust, temperatures of fuel-air mixture were common. Temperatures of flue gases along the boiler, starting from the combustion chamber of the furnace up to the outlet of the boiler, have not experienced any adverse changes in co-firing of mixtures with 5 and 7 wt.% of sawdust compared to temperatures recorded in the process with reference coal, in

the entire range of boiler loads. The results of the temperature of flue gases in the melting chamber of the furnaces (measured by 4 optical pyrometers arranged evenly over the cross section at the outlet of the melting chamber), for various fuel mixtures in the trial run for a maximum load of the boiler are given in fig. 3, points 1-4. The temperature at the end of the furnace (measured by Pt-Rd-Pt thermocouples) that is relevant to the process of ash slugging/fouling in the flame zone threshold and superheaters surfaces in the boiler, is even more favorable (lower) in co-firing mixtures compared to the test with the reference coal, see fig. 3, point 5. So, not only has a negative impact been observed in terms of the temperature field in the boiler in co-firing trials, which could adversely affect the slagging/fouling and the efficiency of the boiler, but the temperature field in the boiler is even more favourable in the co-firing regimes tested. Average temperatures registered by 4 optical pyrometers in melting chamber during trial run for three different fuels and different Boiler loads tested are given in tab. 5.

Table 6 summarizes parameters of primary, secondary and tertiary air, as well as O₂, recorded during trial run for three different fuels and different Boiler loads tested.

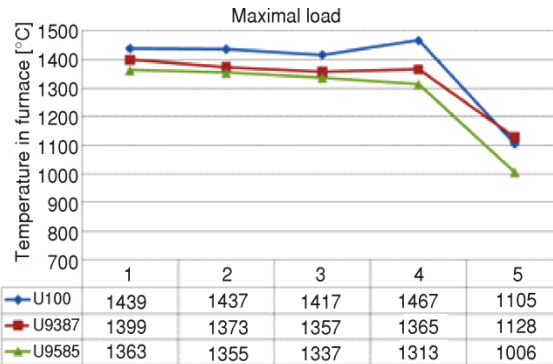


Figure 3. Temperatures at outlet cross-section of melting chamber (points 1-4) and at furnace outlet (point 5) of Kakanj power plant boiler unit 5

Table 5. Average temperatures in melting chamber during trial run on large-scale unit

°C	U93B7	U95B5	U100
Max load	1374	1342	1440
Mid load	1346	1293	1387
Min load	1315	1284	1329

Table 6. Primary, secondary, tertiary air and O₂ during trial run on large-scale unit

	Primary air [m _n ³ /s]	Secondary air [m _n ³ /s]	OFA [m _n ³ /s]	O ₂ * [%]
U93B7				
Max load	41,62	32,03	10,28	3,27
Mid load	41,02	28,54	9,90	3,59
Min load	40,46	25,84	9,51	4,27
U95B5				
Max load	41,13	33,93	10,19	3,02
Mid load	40,55	27,82	9,95	3,34
Min load	40,58	32,90	9,83	3,86
U100				
Max load	38,94	42,95	10,09	2,92
Mid load	37,53	31,97	9,44	3,22
Min load	39,50	31,74	8,51	3,60

* O₂ in flue gas in the second draft of Boiler, above the reheater

Excess air ration in primary zone of combustion (level of coal burners) was kept in the range 0.95-1.09, depended on Boiler load, while total excess air ration (after OFA) was in the range 1.16-1.25.

The condition of the hammer mills, feeders and belt conveyors in all co-firing trials was normal, with no negative indications in relation to the trial with reference coal, which indicates that the test mixtures of coal and sawdust (with 5 wt.% and 7 wt.% of sawdust) can be transported through the coal delivery system without causing adverse operational problems.

Results and Discussion

Results and discussion – Lab-scale tests

Investigated of slagging and fouling-related problems on lab-scale furnace

The laboratory furnace was operated at varying electric power rates, in order to change the gas temperature, and consequently the nature of deposits formed at different temperatures. The temperature ranges for different types of deposits were then determined from the data points obtained during the tests. Evaluation of ash deposits was supported by visuals (photographically), optical observation of the deposits, mechanical acting to the deposits and chemical analysis of the deposits, [7-10]. Six evaluation criteria were applied, as reported in details in [9]. Thus, shape, state and structure of the ash deposit samples are determined on the basis of visual observation (photographically) and optical observation under a microscope. Powdered, soft, hard and molten data points expressing different types of deposits have been elaborately described in [7-10]. Rate of adhesion and cohesion of the ash deposit were determined by physical acting to the ash sample. Rate of adhesion was assessed by observing behaviour of the ash sample formed on a ceramic probe in an air stream coming from an injector. Diameter of outlet cross section of the injector was 3 mm, air flow was 2 l/min, air velocity at outlet cross section of the injector was 4.7 m/s, the distance from the injector to the ash sample on a ceramic probe was 50 mm, and the acting angle was 45°, [7]. Cohesion of the ash deposit was evaluated using laboratory equipment for testing the mechanical properties of materials and recording pressure force and linear deformation of the ash deposits during the tests. Deposition rate was determined in [9], as a mass of the deposit divided by the deposition area and time for all of the tested fuels.

Chemical composition analysis and Ash Fusion Test (AFT) of the deposits were also done to provide information on alkali metals distribution as a function of the type of fuel and the process temperature, [7, 8].

Based on the above presented multi-criteria analysis and according to the procedure given in [9], final evaluation of slagging and fouling propensity for the given kinds of fuel and process conditions is expressed linguistically in the following terms:

- low slagging/fouling,
- moderate slagging/fouling,
- strong slagging/fouling, and
- very strong slagging/fouling.

The data points were then plotted against various coal/sawdust mixture property based indices, to estimate their range limits and general usefulness for Bosnian coal types and sawdust. Figure 4 shows a typical diagram of process temperature–base-acid ratio, as an indi-

cator of slagging/fouling for the co-firing of Kakanj brown coal with spruce sawdust. This has shown that combustion of the tested coal-sawdust mixtures yields no significant increase of ash deposition compared to burning Kakanj brown coal alone at temperatures up to 1250 °C. Above this temperature, ash deposition of the coal-sawdust mixtures was accentuated; ash deposits were melted and then hardened.

Figure 5 shows images of the Lignite-sawdust co-firing probes, recorded by a 2-D hot-stage microscope with a magnification of 100. Formation of the molten ash spheres can be noticed for the Lignite tested at a temperature of 1250 °C, ash sample on a non-cooled ceramic probe (L-1250-non-cooled probe). This phenomenon had not been noticed either for the same fuel at temperature of 1140 °C (L-1140-non-cooled probe) or for the ash sample on a water-cooled metal probe at a temperature of 1250 °C (L-1250-cooled probe). Very similar results were recorded from a blend of 7 wt.% of sawdust and 93 wt.% of lignite.

Even 20 wt.% of sawdust added to the Lignite could not melt the ash deposit on the water-cooled metal probe (L80S20-1250-cooled probe). Conversely, for a coal blend M1A (72 wt.% rate of the Kakanj brown coal) with a lower melting temperature against the tested Lignite, clear formation of molten ash spheres could be noticed on a water-cooled metal probe already at a temperature of 1140 °C (M1A-1140-cooled probe). This process is fully developed for this coal when burned at a temperature of 1250 °C for the ash sample on a non-cooled ceramic probe (M1A-1250-non-cooled probe). This corresponds to the explanation given by Raask [11].

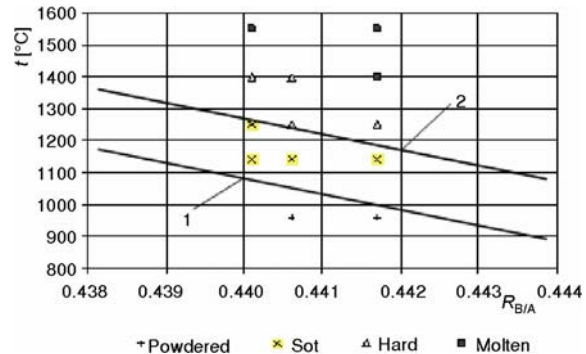


Figure 4. Correlation between base-acid ratio and gas temperature from the lab-scale co-firing tests of the Kakanj brown coal-spruce sawdust, below line 1: low slagging/fouling, above line 2: strong slagging/fouling, between line 1 and line 2: moderate slagging/fouling

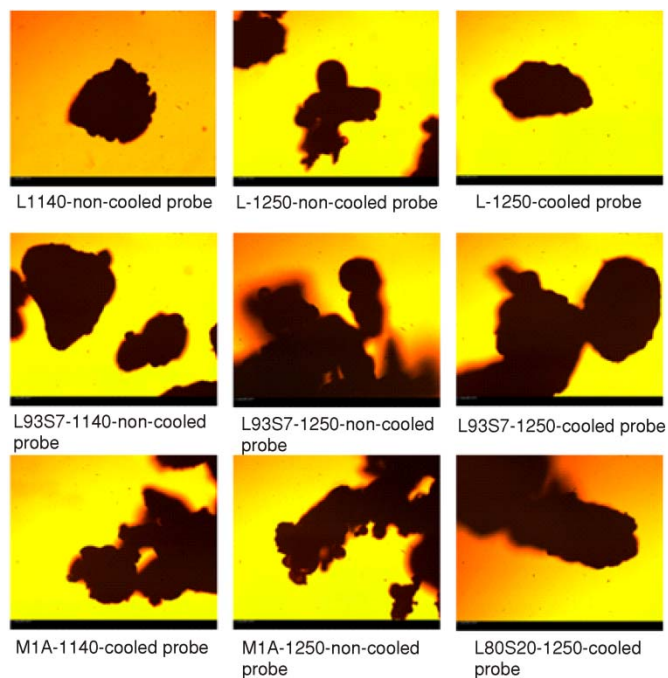


Figure 5. Microscope images of the ash deposits from lab-scale tests of Lignite-sawdust blends

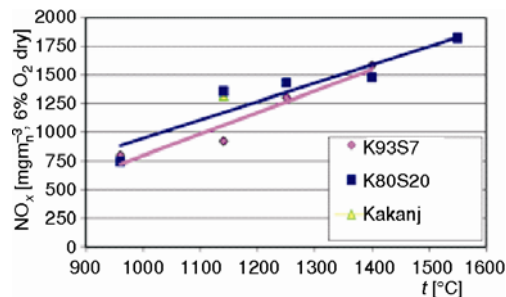


Figure 6. NO_x emissions for the Kakanj brown coal-sawdust, lab-scale co-firing tests, $\lambda = 1.2$.

Both of the coal-sawdust blends tested showed a 50% reduction in NO_x , as the process temperature fell from 1400 °C to 960 °C (reducing from 1600 to 800 mg/m^3 normalized to 6% O_2 dry, at excess air ratio $\lambda = 1.2$). There was, however, an unexpected difference in NO_x emissions for the coal-biomass blends at 1140 °C. The deviation was ascribed to the difference in particle size of the tested blends, as well as to the difference in volatile content of the fuels. No clear relation could be established among the NO_x emissions for the different brown coal-sawdust blends, despite differences in nitrogen content (see tab. 2). Measurements, moreover, confirmed that nitrogen content was not a decisive factor for NO_x emissions for the lignite-sawdust co-firing at the same temperature, either.

Figure 7 shows comparison of NO_x emissions for the lignite blend od Dubrave and Sikulje (L), the mixture of L and sawdust at 93:7 wt.% (L93S7) and the mixture of L and sawdust at 80:20 wt.% (L80S20), at excess air ratio $\lambda = 1.2$.

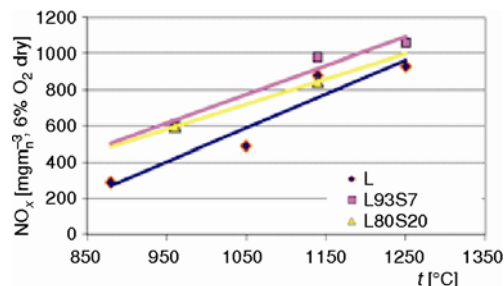


Figure 7. NO_x emissions for the Lignite coal-spruce sawdust, lab-scale co-firing tests, $\lambda = 1.2$

contribute to the NO_x emission decreasing, as reported in [13]. For this reason, the NO_x emissions for the L80S20 blend are lower than for the other two kinds of fuels. On the other hand, more spruce sawdust in the coal/sawdust mixture possibly contributed to the local separation of the slighter spruce sawdust particles in the combustion zone of the furnace which were held longer, against coal particles, in the high temperature zone. This effect increased NO_x emissions during co-firing of coal/sawdust mixtures, resulting in higher NO_x emissions for L93S7 mixture compared to the lignite alone. These results are in line with those reported in [13, 14]. A comparison of the NO_x emission values obtained during co-firing of the brown coal-spruce sawdust, fig. 6, with those obtained during co-firing of the lignite-spruce sawdust, fig. 7, under the same conditions, shows NO_x emission increase of 25 to 30%

NO_x emissions from lab-scale tests

Figure 6 presents the NO_x emissions in mg/m^3 (as NO_2) at 6% O_2 dry for the brown coal-sawdust blends tested on lab-scale furnace. The results are in line with the Zerkowski-model of flame temperature impact on NO_x formation, as reported in [6]. Very high NO_x emissions are also noted at 1550 °C (1800 mg/m^3 at 6% O_2 dry), due to thermal NO formed at temperatures above 1400 °C, according to the Zeldovich-mechanism.

Principally, the highest emissions were measured during test of L93S7 coal/sawdust mixture (with N = 0.47% and Volatiles of 27.9%), which were slightly higher compared to both lignite alone L (N = 0.48% and Volatiles of 24.32%) and L80S20 blend (N = 0.45% and Volatiles of 34.55%). This trend of NO_x emissions during co-firing of the lignite-sawdust could be explained by the following facts and thesis: Adding more biomass to the basic lignite decreases Nitrogen content in the coal/sawdust mixture and increases the Volatiles content. Both

for co-firing of the brown coal-spruce sawdust. This finding was ascribed to the higher (almost double) content of nitrogen in the Kakanj brown coal-spruce sawdust mixtures against the Lignite-spruce sawdust mixtures, tab. 2.

In regards to the impact of the excess air ratio on the emissions, it was found to exert a strong influence on the NO_x emissions for both the tested basic coals and co-firing fuels, that is in line with results given in [13, 14].

SO₂ emissions and sulphur capture rate

Considerably less SO_2 was measured for the brown coal-sawdust mixtures than for the coal alone. Thus, at 1140 °C, there was 15% less SO_2 for the K93S7 mixture and 28% less for the K80S20 mixture than for Kakanj brown coal alone, [7, 8]. The main reason for this is the lower sulphur content in the coal-sawdust mixture against the coal alone; see tab. 2, and also, increasing Ca/S molar ratio with the addition of spruce sawdust to the coal/sawdust mixture.

With regard to the lignite-sawdust co-firing, the lowest SO_2 emission was measured for the L80S20 mixture ($\text{S} = 0.65\%$, $\text{Ca/S} = 0.863$), fig. 8. Approximately 20% higher SO_2 emission was measured for the L93S7 mixture ($\text{S} = 0.71\%$, $\text{Ca/S} = 0.897$). However, it is interesting that for the basic fuel-lignite L ($\text{S} = 0.73\%$, $\text{Ca/S} = 0.899$), emission of SO_2 at lower process temperatures (880 and 960 °C) is lower than lignite-spruce sawdust mixtures. This can be ascribed to the more convenient Ca/S molar ratio for the lignite alone, which increases sulfur bonding to the calcium from the ash at lower temperatures.

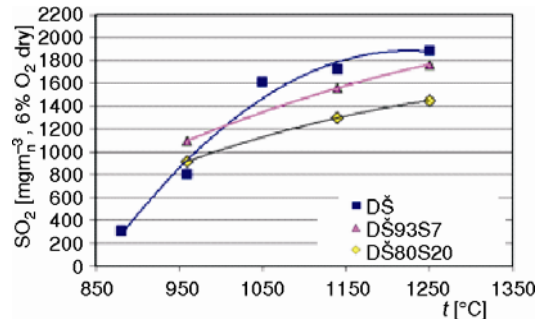


Figure 8. SO_2 emissions for the lignite-spruce sawdust, lab-scale co-firing tests, $\lambda = 1.1$

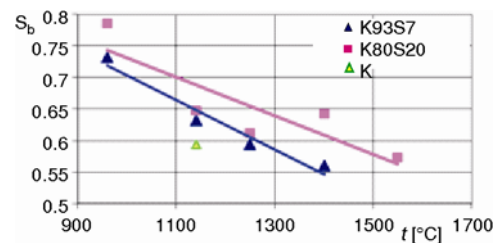


Figure 9. Sulfur capture rate as a function of process temperature for Kakanj brown coal-spruce lab-scale co-firing tests, $\lambda = 1.2$

This thesis is also supported by the results of sulphur capture rate (S_b) for the co-firing fuel test matrix, fig. 9 and fig. 10, showing higher values for the brown coal-sawdust mixtures. Sulphur capture rate is set here as rate of bonding of SO_2 generated immediately in the furnace with the basic oxides from the ash, predominantly CaO . It can be noticed also from the figures that sulphur capture rate decreased for all tested fuels, as the temperature rose. The reason is the well-known phenomenon that sulphur bonds better to CaO particles at lower temperatures [7-9].

Finally, an increase in the sulphur capture rate was noted for the Kakanj coal-spruce sawdust co-firing for all temperature regimes, as the Ca/S molar ratio rose – *i.e.* as spruce

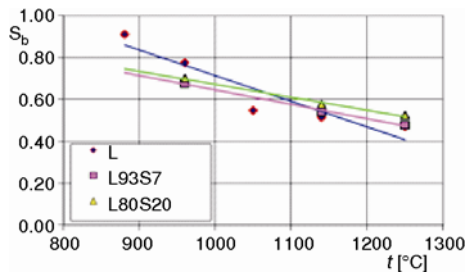


Figure 10. Sulfur capture rate as a function of process temperature for the lignite-spruce lab-scale co-firing tests, $\lambda = 1.1$

finding at higher temperatures was ascribed to the lower content of silica oxide in ash of the spruce sawdust ($\text{SiO}_2 = 21.3\%$) compared to the lignite ($\text{SiO}_2 = 49.88\%$), mitigating the inhibition action of SiO_2 to the sulphur capture at higher temperatures for co-firing of lignite-spruce sawdust.

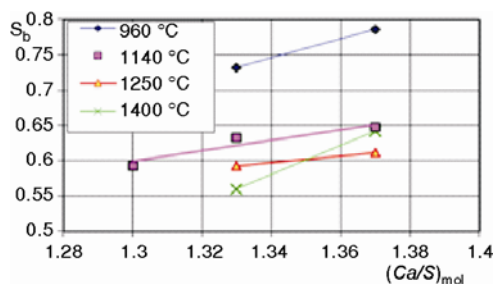


Figure 11. Sulphur capture rate as a function of Ca/S and process temperature for lab-scale co-firing tests of the Kakanj brown coal-spruce sawdust, $\lambda = 1.2$, $(Ca/S)_{\text{mol K}} = 1.30$, $(Ca/S)_{\text{mol K93S7}} = 1.33$, $(Ca/S)_{\text{mol K80S20}} = 1.37$

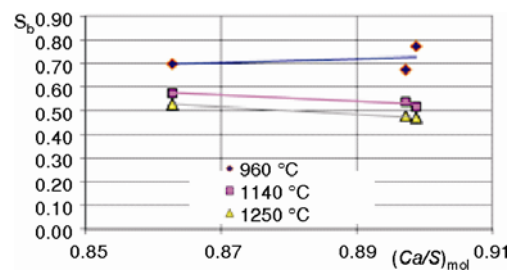


Figure 12. Sulphur capture rate as a function of Ca/S and process temperature for lab-scale co-firing tests of the lignite-spruce sawdust, $\lambda = 1.2$, $(Ca/S)_{\text{mol DŠ}} = 0.899$, $(Ca/S)_{\text{mol DŠ93S7}} = 0.897$, $(Ca/S)_{\text{mol DŠ80S20}} = 0.863$

Results and discussion – tests on Kakanj power plant boiler unit 5

Slagging/fouling assessment based on the trial run

In the planned pauses between the fuel trials during the trial run, a detailed inspection of the state of boiler heating surfaces was carried out in terms of identification of slagging/fouling of the boiler surfaces. Sampling of ash deposits was done in order to complete chemical analysis and to examine the detailed distribution of alkaline components in the composition of deposits.

Deposits taken from the melting chamber and the superheater in zone of the furnace outlet are compared for different kinds of fueling, and analysed for their chemical composition. A comparison of deposits taken from the superheater PP2A placed at the furnace outlet is given in fig. 13.

The conclusion is that there is no deterioration in the form of deposits in the co-firing trials compared to the trial of “reference coal”. On the contrary, deposits from the co-firing trials are more brittle. Specifically, the form of ash deposits in this zone of the

sawdust was added to the Kakanj brown coal, fig. 11. This represents another synergy effect relating to SO_2 emission for the co-firing of brown coal with sawdust, [8]. This additional SO_2 reduction effect could not be identified for the lignite-spruce sawdust co-firing. Actually, fig. 12 shows that as spruce sawdust was added to the lignite tested, accompanied in this case with decreasing Ca/S molar ratio, effect of better bonding of sulphur was noticed only at higher temperatures (1140 and 1250 °C), while at temperature 960 °C this effect failed. This

boiler (the furnace outlet) is normal and acceptable; they are more brittle and easy-to-remove. They do not represent a threat to the stability of operation or the efficiency of the boiler. This correlates with the findings of the laboratory tests and the suggestion that deposits will not be a problem if 7%w sawdust is blended with coal used in large power stations.



Figure 13. Ash deposits taken from superheater PP2A, fuel trials U100, U95B5 and U93B7

The base-acid ratio for the ash deposits is given in fig. 14. The results confirm the findings of the condition of the ash deposits in the region of the furnace outlet (Superheater PP2A), which is “better” in the co-firing trials than the deposits from the trial of “reference coal”. This corresponds to a lower (more favorable) base/acid ratio for deposits taken from SH PP2A after the co-firing process, fig. 13. The results in fig. 14, and the findings on the deposits condition described above, indicate that co-firing regimes U95B5 and U93B7 produce a more intensive redistribution of alkaline components in the slag in the melting chamber, which has a consequential beneficial effect on the deposition of ash on the superheater surfaces of boiler TPP Kakanj unit 5.

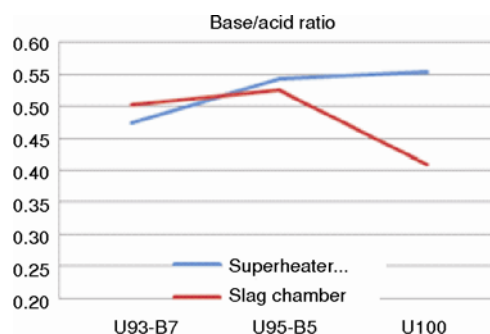


Figure 14. Base/acid ratio for the ash deposits taken from the Boiler TPP Kakanj unit 5

NO_x emissions during the trial run

Figure 15 shows the NO_x emissions registered in the Teleperm XP system (sensors in the channel behind dust filter and flue gas fan), as well as NO_x emission registered on monitoring system (sensors in the channel before the chimney) for the different fuel trials and different boiler loads. Only slight change in NO_x emissions can be noticed with the change of fuel, and there is no clear correlation between the influence of adding biomass to the emission of NO_x, which is consistent with experimental research described above, as well as with many findings in the world on the phenomenon of the influence of biomass on emissions of NO_x, see [9-11]. In any case, it can be concluded that there is no deterioration of NO_x emissions in cofiring process.

Dust emission

Dust emission on TPP Kakanj unit 5 in cofiring processes is on level of values in campaign „reference coal“, it is low; at <18 mg/m³ at 6% O₂ dry for campaign U95B5, and at

$<10 \text{ mg/m}_n^3$ at 6% O_2 dry for campaign U93B7. Moreover, electro static precipitator (ESP) as first plant in line of combined system for dust cleaning on TPP Kakanj unit 5 which consisted of ESP and baggy hybrid filter, works better than in campaign „reference coal“–U100. Namely, values of currents between electrodes of the ESP are more than twice higher during cofiring regimes against regime with referent coal, fig. 16. This means that cofiring with spruce sawdust effects positively to the operation of ESP in case of TPP Kakanj Unit 5.

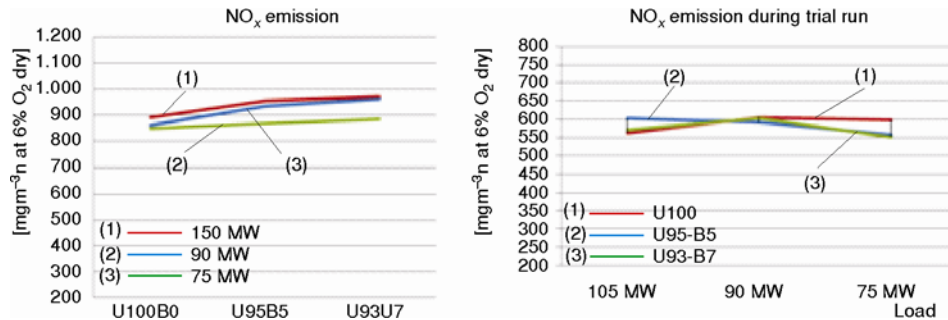


Figure 15. NO_x emission registered by: XP teleperm system of the unit (sensors in flue gas duct behind dust filter and fle gas fan)-figure left, Monitoring system of the unit (sensors in flue gas duct before Chimny)-figure right (color image see on our web site)

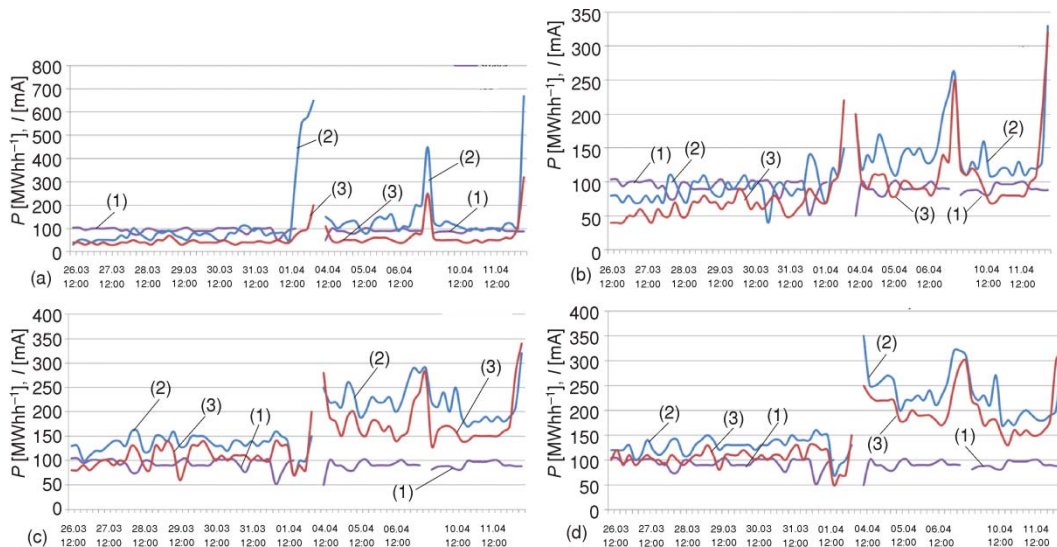


Figure 16. Values of currents in fields of ESP during trial run on TPP Kakanj Unit 5: operation with referent coal (date period: 26.-31.03.2012.), cofiring operation with U93B7 (date period: 04.-06.04.2012.) and cofiring operation U95B5 (date period: 10.-11.04.2012.) (a) Field 1, (b) field 2, (c) field 3, (d) field 4; (1) – load, (2) – curent left, (3) curent right (color image see on our web site)

Conclusions

Experimental research on a 20 kW PF flow furnace was carried out to investigate ash-related problems and emissions during co-firing Bosnian brown coal and lignite with

spruce sawdust and to optimize percentage of sawdust in the coal-sawdust fuel mixtures for operation in large-scale utility. The trials on lab-scale furnace show that a blend of 7% by weight of sawdust added to the Kakanj brown coal produces no risk to the combustion process but produces benefits in reduced emission levels. Combustion of the coal-sawdust mixtures tested yields no significant increase in ash deposition compared to the coal alone at temperatures up to 1250 °C. Above this temperature, ash deposition is accentuated for the coal-sawdust mixtures. For the process temperatures suitable for slag tap furnaces – *e.g.* temperatures around 1550 °C, continuous slag flow can be expected over refractory lining of slag chamber when the co-firing blend with 20 %w of the sawdust was used rather than when the Kakanj brown coal on its own was used. The measurement of SO₂ emissions during the lab-scale co-firing tests showed considerable decrease of SO₂ emission when the spruce sawdust is fired with the coals. In addition to the reduction of SO₂ due to the lower sulfur content in the coal/sawdust mixtures tested, the brown coal-sawdust co-firing generated a further reduction due to the higher sulfur capture rate than for coal alone in all temperatures tested. From the other side, it was found that content of nitrogen in the fuel was not a decisive factor relating to NO_x emissions. Thus, volatiles content and characteristics of the particles and their mixing in the fuel blend, effecting the residence time in the combustion zone, were identified as important factors which influenced NO_x emission. It was not possible to identify clearly the influence the sawdust content in the co-firing blend had on NO_x emissions during the lab-scale tests performed.

On the basis of recommendations from laboratory research, the trial run at the Kakanj power station unit 5 (110 MW_e) involved replacing 5% and 7% by weight of brown coal with Spruce sawdust. The fuel mixture was introduced into the furnace over the hammer mills and low-NO_x coal burners. Compared to the trial with 'reference coal', co-firing regimes come up with more intensive redistribution of alkaline components in the slag in the melting chamber, which has a consequential beneficial effect on the deposition of ash on the superheater surfaces of the boiler at TPP Kakanj Unit 5. Deposits in the zone of the furnace outlet were brittle and easy-to-remove and, therefore, do not represent a threat to the stability of the operation and efficiency of the boiler. This is in correlation with the findings from laboratory tests and the suggestion that no deposit-related problems will occur if till 7% by weight of sawdust is blended with the coal burned in large power stations. Only a slight change in NO_x emissions was noticed with the change of fuel during trial run on Boiler, and there is no clear correlation between the effect of adding sawdust and the NO_x emissions, which is consistent with the laboratory research. The outcome of the experimental tests confirms the feasibility of using till 7wt.% of sawdust in combination with the coal without any risk to the efficiency of the unit, its combustion process, the unit load flexibility, and with the benefits of emissions reductions. Furthermore, they show that no modification to the existing coal transport system and boiler equipment is necessary.

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